

A Methodology for Evaluating Demining Personal Protective Equipment for Antipersonnel Landmines

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ABSTRACT

The human toll from antipersonnel (AP) mines is large. To decrease the human toll from demining, protective equipment should be used. For comprehensive protection, the demining personal protective equipment (PPE) may include head/face protection, and thorax protection that may offer the potential for substantial protection against fragments, blunt force trauma, burns, and other consequences of mine blasts. However, without some objective procedure to evaluate the risk of injury while wearing protective gear, the protection provided by such demining equipment is unknown and may actually exacerbate certain types of injury.

The goal in the current study is to develop an objective test methodology to evaluate the risk of human injuries from mine blasts while wearing a PPE. This methodology will include protected and unprotected subjects and will indicate the relative levels of protection for subjects wearing different protective equipment. The basis of this test procedure is an instrumented biofidelic surrogate. A Hybrid III dummy, widely used in the automobile industry, was selected for this testing. The Hybrid III dummy is anthropometrically similar to humans, with several sizes representing a wide range of human anthropometry. Another element of this technique includes an injury risk evaluation using a human or animal injury model. Widespread use of this technique has saved thousands of lives per year in the automobile industry.

This study used an unprotected dummy to validate the test methodology. To minimize the potential for experimental variation, these PPEs were evaluated against three levels of simulated mines, 50 g, 100 g, and 200 g C-4, and a widely fielded antipersonnel mine, the PMN. A simple and inexpensive test fixture was developed that allowed accurate positioning of the dummy surrogate to within ± 3 mm. Both the kneeling and the prone demining positions were evaluated in 102 tests that were performed to evaluate test repeatability and robustness of dummy response. The dummy response under blast loading showed good repeatability for multiple shots under the same experimental condition. Further, for both the unprotected and protected dummy, the severity of the dummy response was well correlated with the charge mass in the mine; standard injury criteria indicated that the risk of injury increased with increasing charge mass. Also, the dummy response in the prone vs. kneeling position showed the dramatic effect of the conically-shaped blast pattern. For a given distance, there is a far less severe dummy response in the prone than in the kneeling position.

I. INTRODUCTION

The human toll from antipersonnel mines is large. Though estimates vary on the number of mines deployed worldwide [UN-2000], an estimated 20,000 civilians die each year from landmine explosions. Thousands more are wounded or maimed. As there is still no inexpensive and reliable mechanical technique for detecting and removing antipersonnel mines, human deminers will be used for the foreseeable future to protect the general population from the menace of landmines.

To decrease the human toll from demining, protective equipment should be used. For comprehensive protection, the personal protective equipment (PPE) demining equipment may include head/face protection, thorax protection, and extremity protection including gloves and boots as shown in Figure 1. This suit offers the potential for substantial protection against fragments, blunt force trauma, burns, and other consequences of mine blasts. However, *without some objective procedure to evaluate the risk of injury while wearing protective gear, the design of such demining equipment is guesswork.* Indeed, without an effective injury evaluation technique, protective equipment may exacerbate certain types of injury. For example, the introduction of body armor in Northern Ireland for protection against blast fragments may have increased the potential for blast lung injuries [Mellor-1989].



Figure 1: Demining PPE (Photo Courtesy Med-Eng, Inc.)

One technique that has been shown to be effective in the automobile industry is the use of an instrumented surrogate (dummy) to evaluate the risk of injury from blunt trauma in automobile crashes. Elements of this technique include:

- Biofidelic surrogate – a dummy that is robust, gives a repeatable physical response, and produces a response that is appropriately human-like. A dummy may be physically very simple and may only represent a part of a human. For example, an instrumented beam

has been used successfully to represent an arm [Bass-1997]. However, dummies may be very complex, such as the anthropomorphically-correct dummies being developed for the automobile industry. Generally, a surrogate should be as simple as possible while still representing the relevant human response.

- Engineering measurement – a physical parameter such as force or acceleration that may be used to quantify the physical response of the dummy. Dummies may be instrumented to produce accepted or proposed injury criteria.
- Injury risk evaluation – a correlation between an engineering measurement and some injury model. For example, in frontal thoracic blunt impacts, an injury threshold of 60 times the force of gravity is used in the automobile industry.
- Validation by injury model – a correlation between the injury risk evaluation and a physical model of injury. An injury risk model is without value without successful validation using 1) epidemiology or physical reconstruction of an actual injury event, 2) an animal injury model, or 3) a cadaveric human injury model as shown in Figure 2. Development of a relationship between a robust surrogate for injury and a validated injury model is crucial in the success of this approach.

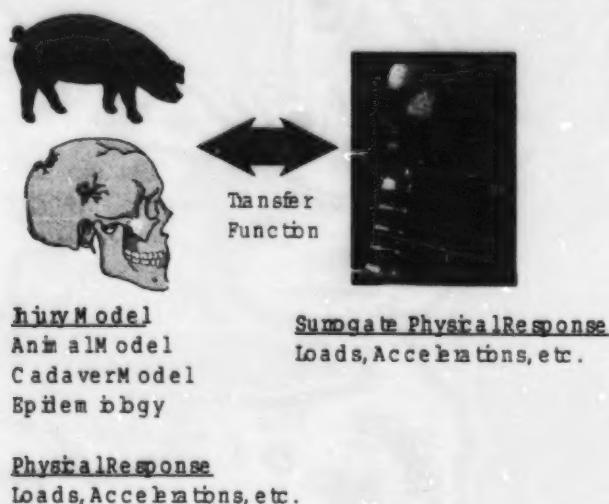


Figure 2: Development of Surrogate Injury Model

Two other important elements of injury simulation may be adapted from those used in automobile testing; use of injury epidemiology to direct testing and injury modeling and use of realistic test conditions. Both limit the risk that an injury simulation is an academic exercise, not applicable to real world conditions.

Widespread use of this technique has saved thousands of lives per year in the automobile industry. Indeed, all automobiles and safety restraints, including air bags, are evaluated using dummy surrogates. As there are similarities in human blunt trauma in an automobile crash and in a blast event, aspects of this technique may be adapted for use in determining injury from mine blasts. The current study builds on several previous test series using Hybrid III dummies

and simulated mines to evaluate the performance of demining PPEs. These test series include work performed under the auspices of the Canadian Center for Mine Action Technologies (CCMAT) [c.f. Bergeron-2000] and the U.S. Army – Communications-Electronics Command (CECOM) Countermine [c.f. Chichester-2000].

In subsequent sections, the test methodology, dummy, positioning instrumentation, and test results are discussed. These are followed by conclusions on the suitability of this test methodology to repeatably characterize demining trauma with and without PPEs.

2. OBJECTIVE TEST METHODOLOGY

The goal in the current study is to develop a procedure to evaluate injuries from mine blasts, borrowing tools from existing techniques when appropriate. This will result in an objective test criterion for the evaluation of the injury risk of a human wearing a PPE. It will allow this injury risk evaluation for protected or unprotected subjects and will indicate the relative levels of protection for subjects wearing different protective equipment.

For decades, work has been performed on human injury from blunt trauma in the automobile field. Simulated automobile crashes are performed, and the response of the dummy surrogate is taken to represent the response of a human in that crash scenario. This dummy response may be used in an injury model to assess the risk of injury for that crash scenario.

The tools used in the automobile industry, however, may not be directly applicable to mine blasts for two reasons. First, automobile crashes and mine blasts are substantially different physical phenomena. While both automobile crashes and mine blasts may involve blunt head and chest trauma, mine blasts may have substantial shock wave effects, burns, and other blast phenomena. Second, the events may occur on significantly different timescales. Automobile crashes have injury timescales of approximately 5-100 milliseconds, but injuries in mine blasts may occur 10 to 100 times faster. These timescales have an effect on dummy surrogate response, and the timescale of mine blast injuries may be outside the validity of the injury models used in the automobile industry. So, tools used in the automobile industry must be adapted for use in mine blast testing to effectively assess the risk of injury while wearing protective PPEs.

2.1 Epidemiology

Another important element in the effective design and evaluation of protection from injury is the epidemiology of the occurrence of those injuries in the field. Initial efforts to categorize injuries from humanitarian deminers [Landmine-2000] have identified the most significant injuries from mine blasts. Epidemiology, however, is a moving target and future efforts to categorize ongoing injuries and their causes are crucial. For instance, the use of protective features may change the types of injuries experienced and could warrant changes in the focus of injury protection. A clear example of this came with the widespread use of automobile driver-side air bag restraints. Use of such systems resulted in a substantial decrease in fatal head and thorax trauma, but also led to an increase in the importance of debilitating leg injuries.

The types of injuries encountered in a number of demining incidents have been summarized in a groundbreaking report [Landmine-2000] as shown in Figure 3. Fatal injuries include blunt trauma to the head and chest, including blast lung, shock, and multi-system trauma. Blast injuries may also include blast-induced trauma to hearing, burns, and trauma from whole body translations with injury patterns similar to falls. To provide a realistic assessment of injury from mine blasts, injuries from these body regions, especially blunt trauma that may arise while protected, must be included in the injury risk assessment.

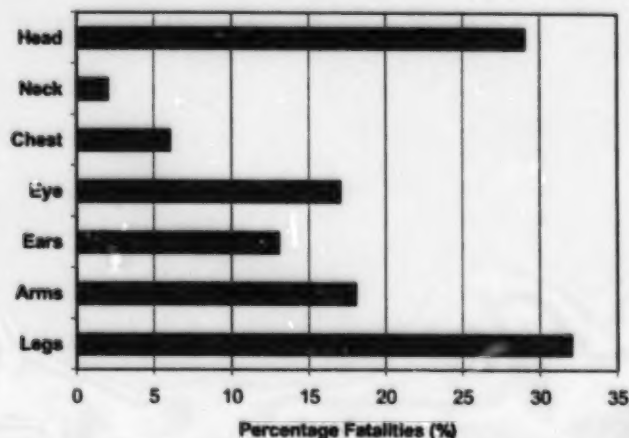


Figure 3: Injuries from AP Landmines Sustained in Demining Incidents [Landmine-2000]

2.2 Mines

Modeling the mine blast itself is a complicated issue. Nominally identical mines may have widely different behavior, and blast characteristics may change considerably depending on soil and environmental conditions. Also, real mines may be difficult to obtain in quantity and to handle safely. To develop an objective test procedure, a test condition should be realistic yet repeatable, a balance that limits the number of tests and cost necessary to effectively characterize the performance of protective equipment. This suggests that mines should be simulated with a relatively well-characterized plastic explosive and should be implanted in a well-characterized soil. Several blast energies may be used to simulate the range of energies expected with actual mines.

In this study antipersonnel landmines were simulated using 50, 100, and 200 grams of C-4 packed in plastic containers that simulate deployed landmines as shown in Figure 4. These charge sizes were selected to best represent the effects of the broad spectrum of actual antipersonnel mines worldwide and to provide better repeatability from test to test [Bergeron-1999]. The simulated mines were initiated using standard high voltage detonators. To provide a repeatable and well-characterized environment for the mine blast, a 2 ft. x 2 ft. x 2 ft. steel open top box was placed within the base of the positioning apparatus in front of the dummy and was filled with medium-grain building sand. The mines were buried 2 cm below the surface of the sand and were statically detonated. Damaged sand was removed after each shot and replaced.

To assess mine performance relative to an actual mine, tests were performed using a statically detonated PMN mine as shown in Figure 5. A free field pressure sensor was used to record the pressure time history of the blast at a location $124 (\pm 1)$ cm horizontally from the center of the mine at the level of the ear as shown in Figure 6. Except for the 50 g mine, each condition had large numbers of mine shots and relatively small spreads in both pressure peaks and integrated impulse. In addition, pressure peaks and integrated impulse were statistically different between the three levels of simulated mine. Further, both pressure peak and impulse from the 200 g mine were very similar to the PMN mine, suggesting similar free field behavior for the actual and the simulated mines. These results give an initial indication of robustness of response, repeatability, and differentiation between three levels of charge.

One significant effect of the confinement of the blast by the soil in both the simulated mine and the PMN mine is the existence of a 'blast cone' as seen clearly in Figure 7 [c.f. Bergeron-2000]. This is a conical region above the mine in which the blast ejecta and streaming flow is substantially more forceful than outside this region. This blast cone makes the effect of position of the dummy in the field extremely important. Further discussion of the physical effects of mine performance within the blast cone is reported below.

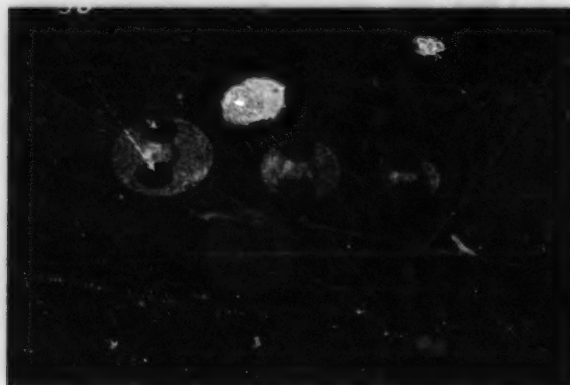


Figure 4: Simulated Mines

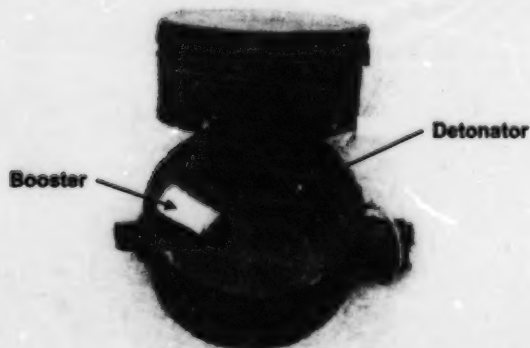


Figure 5: PMN Mine

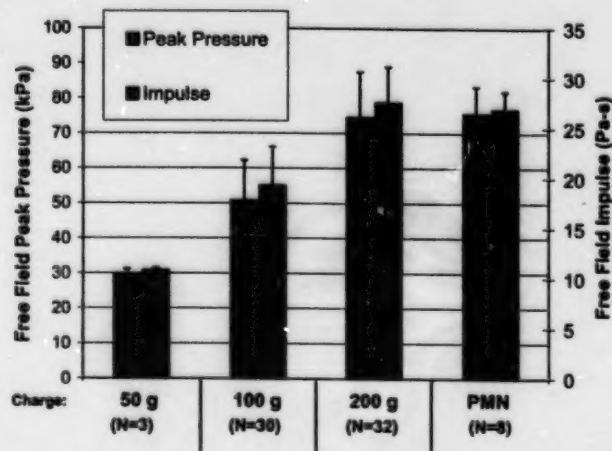


Figure 6: Peak Pressure and Impulse from Reference Pressure Gauge

2.3 Dummy and Instrumentation

Simulation of a realistic test condition is especially important in mine blast testing. A high-speed photograph of a simulated mine blast with a dummy surrogate is shown in Figure 7. The force on a human chest or head is related to the pressure from the blast wave and streaming flow from the blast ejecta. Since pressure falls rapidly from the blast and the streaming flow is highly directional, the dummy surrogate position in the blast is vitally important in a realistic simulation. A field survey found that 91% of demining blast incidents occur with the victim within 1 meter of the mine [Landmine-2000]. It is clear, however, that close enough to a large mine blast there may be substantial injury using any personal protective equipment. So, a balance must be maintained between the desire for test realism and the desire to evaluate the worst case in mine blast injuries.



Figure 7: Simulated Antipersonnel Mine Blast with Hybrid III Surrogate

Two pedestrian version 50th percentile male Hybrid III anthropomorphic dummies, denoted (A) and (B), were used in this test series. One is shown in Figure 7. These dummies, used in automobile crash testing, are particularly useful in estimating the risk of frontal blunt trauma and

are validated for frontal blunt impacts to both the head and the chest. In addition, a Hybrid III 5th percentile female dummy was used in selected shots to represent deminers smaller statures [Bass-2000]. The dummies were placed in each of two positions, kneeling and prone, as discussed in the following section. Tests were performed using unprotected dummies and dummies in each of five humanitarian demining PPEs. Further information on the generic performance of each suit is presented in Chichester et al [Chichester-2001].

The Hybrid III dummies were instrumented with acceleration-sensing transducers, force-sensing transducers, displacement transducers, and pressure transducers to evaluate head, neck, and thoracic trauma as shown in Table 1. The data from these transducers may be used with accepted injury thresholds and risk functions to determine the risk of injury in a given test condition as reported below. Instrumentation data was sampled at 200 kHz with a 40 kHz antialiasing hardware filter.

Transducer	Location	Evaluation	Sensor
Accelerometer (Triax)	Head Center of Gravity	Head Blunt Trauma	Endevco 7270A-6k
	Chest Center of Gravity	Thorax Blunt Trauma	Endevco 7270A-6k
Load Cell	Upper neck	Neck Blunt Trauma	Denton Upper Neck Load Cell
Accelerometer	Sternum	Thorax Blunt Trauma	Endevco 7270A-6k
Displacement Transducer	Sternum	Thorax Blunt Trauma	Servo 14CB1-2897
Pressure Transducer	Thorax: skin surface, between 3 rd and 4 th rib	Thorax Blast Lung	Kulite XCQ-093-500A Kulite LQ-125-500A
	Head, skin surface, mounted laterally at ear location	Ear Blast Damage	Kulite XCQ-093-500A
Thermocouple in Skin Simulant	1 each, thorax, head, hand	Thermal Blast Damage	Omega 0.5 mil and Omega 3 mil bare wire gages
Pressure Gauge	Free field at the same x y locations as ear and thorax	Free Field Pressure	PCB 102-A04

Table 1: Instrumentation and Trauma Evaluation

2.4 Test Condition and Test Fixture

Accurate positioning is crucial to ensure repeatability of response and to allow an effective evaluation of the performance of a demining PPE for two principal reasons. First, the strength of the mine blast falls rapidly with distance from the mine in the near field. Second, soil confinement of the mine blast imposes a 'blast cone' which includes the most forceful, streaming component of the blast. The test fixture constructed for this study is based on a design produced by a U.S. - Canadian collaboration reported by Nerenberg et al [Nerenberg-2001] used in previous PPE testing as shown in Figure 8.

Accurate positioning of the dummy relative to the center of the mine was performed using a measurement fixture, also shown in Figure 8 for the kneeling position, that allows repeatable

positioning of both the mine and the dummy to within approximately ± 3 mm of fixed reference points. The measurement fixture incorporated two sliding measurement arms to locate the reference points at the dummy nose and sternum center in a rectangular coordinate system with the origin at the center of the mine with an accuracy of approximately ± 1 mm. To ensure accurate mine placement relative to the test fixture, a cylindrical form on the base of the measurement unit was used to create a hole in the sand for mine placement. The form fit inside a sleeve, which remained when the measurement fixture was removed for mine placement. After the mine was placed in the sleeve, the sleeve was removed, and the mine was covered with 2 cm of sand (flush with the side rails of the positioning fixture). Three forms with matching sleeves were used, one for each simulated mine size. The largest simulated mine size matched the PMN mine.

Both the kneeling and the prone positions were selected to establish a baseline position that was severe enough to produce a significant risk of injury in the unprotected dummy, but not too severe that the dummy could be damaged or that the most protective of the PPEs could not reduce the injury criteria values. The nominal kneeling position, evaluated using an accurate three-dimensional contouring tool, is shown in **Figure 9**. The dummy was positioned using chains attached to the upper spine, which allow free motion to the rear under a mine blast. The dummy maintains lower extremity position using normal joint friction. After positioning the unprotected dummy in the kneeling or prone position, the measurement fixture was used to record distances from the center of the mine. For the dressed tests, after the nose and sternum were set in place, the dummy was dressed in the PPE. The body armor and visor were then set to selected distances from the mine. For the kneeling position, the radial nose-to-mine distance was set to 70 cm at an angle 65° from the mine with x (horizontal) and z (vertical) coordinates as shown in Table 2. The radial sternum-to-mine distance was set at 64 cm with coordinates shown in Table 2.

	Nose to center of mine distance		Mid sternum to center of mine distance		Nose to Mine Angle (from Horizontal)
	X (cm)	Z (cm)	X (cm)	Z (cm)	
Kneeling	63.4	29.6	42.2	48.7	65°
Prone	30.5	33.2	NM	19	48°

Table 2: Coordinates for Positions Tested (NM = Not Measured)

For the prone position shown in **Figure 9**, the positioning fixture is not used. Instead, the dummy is balanced on the elbows, and position is maintained by normal joint friction. To produce potentially injurious head accelerations in the unprotected dummy, the radial distance is significantly decreased to 45 cm, at an angle of 48° vertically from the mine. Coordinates are shown in Table 2.

The Hybrid III dummy was modified to increase the range of motion in both the lower cervical spine and the lower lumbar spine to enable the dummy to assume a realistic prone position with approximate biofidelic spine extension. Human range of motion in extension is approximately 35 degrees in the lumbar spine, approximately 25 degrees in the thorax, and approximately 50 degrees in the neck. Since the Hybrid III dummy has a limited number of locations to add

additional extension, a 30 degree wedge was inserted above the flexible lumbar spine. In addition, the slot in the adjustable lower neck mount was elongated to allow a total of 22.5 degrees in extension from the neutral position. Use of these adjustments produced an approximately realistic Hybrid III dummy prone position as shown in Figure 9.

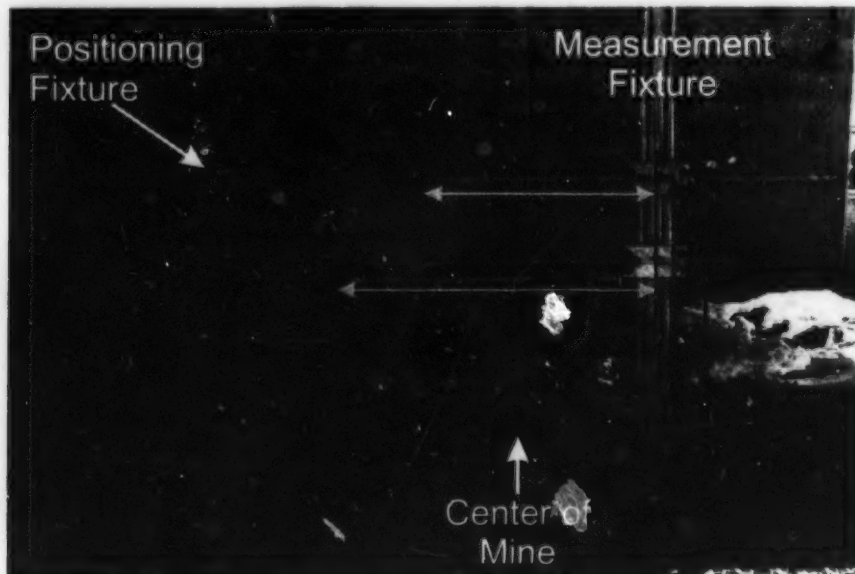


Figure 8: Kneeling Dummy with Positioning and Measuring Fixtures (Note: Positioning Fixture Not Used for the Prone Position)

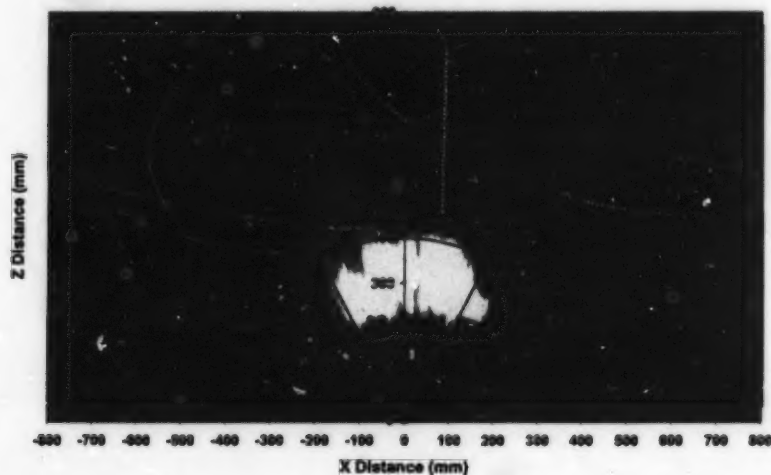


Figure 9: Nominal Kneeling and Prone Positions Relative to the Center of the Mine - Radial Lines at 30° and 60°

Post-shot damage assessment was conducted immediately following the shot and initial safety period. The initial damage assessment included photographic documentation; inspection of suit, dummy, and instrumentation; and preliminary evaluation of acquired data. The dummies were dressed in woven cotton trousers and shirts beneath the PPE to enable detection of fragmentation penetration. Each piece of PPE was thoroughly examined for tearing, fragment penetration or partial penetration, and overall integrity. Damaged PPE components were replaced as required; helmets and visors were replaced every shot.

3. RESULTS

Sensor data from the mine blasts into the unprotected dummies was examined for repeatability and dummy to dummy variation. This study evaluated principally the unprotected tests, the protected tests are reported in a separate study [Chichester-2001]. The principal areas reported below are head blunt trauma, neck blunt trauma, thoracic blunt trauma, and burns. A key issue in the evaluation of the blunt injury data is whether the standard injury criteria for the Hybrid III dummies may be successfully used since the dynamic time scale of the blast is different than that of automobile crashes.

3.1 Head Blunt Trauma

As discussed above, fatalities from head injuries are very significant in actual mine blasts. These injuries may be caused by environmental fragmentation, direct blast impingement on the head, or blast forcing protective headgear into the head. One injury criterion commonly used with the Hybrid III dummy head/neck complex is the Head Impact Criterion (HIC) for concussive head injury [Versace-1971] based on the Wayne State Concussive Tolerance Curve [Patrick-1963]. HIC includes the effect of acceleration time history $a(t)$ and the duration of the acceleration. HIC is defined as:

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} \right\}_{\max}$$

where t_1 and t_2 are the initial and final times (in seconds) of the interval during which HIC attains a maximum value. So, HIC includes the effect of head acceleration and duration; when the acceleration is expressed in g's, a HIC value of 1000 is specified as the level for onset of severe head injury. The maximum time duration of HIC is limited to a specific value, usually 15 ms. Physically, HIC predicts that large accelerations may be tolerated for short times and is evaluated using the head triaxial accelerometer at the head center of gravity. This standard is often used to assess head injury using Hybrid III dummies in frontal impacts. However, HIC is based on human cadaver and animal impact data with durations that are usually 5 milliseconds or greater, with extremely limited data less than 1 millisecond in duration. The acceleration effects of near field blasts are often shorter than 5 milliseconds, raising serious questions about the applicability of the usual injury criteria to mine blast head trauma.

HIC values obtained for unprotected, kneeling dummies are shown in Figure 10 for mine blast strengths of 50 g C-4, 100 g C-4, and 200 g C-4. These HIC values for repeated tests show good

repeatability among charge sizes and excellent correlation between Dummy A and Dummy B. In subsequent analysis, sensor data from these dummies are lumped. The differences in HIC between charge sizes are statistically significant ($p < 0.01$) with increasing response for increasing charge size. Kneeling and prone conditions were selected to produce roughly equivalent head response for an unprotected dummy. However, the prone position is approximately 25 cm closer to the center of the mine.

For the usual 1650 Hz filter used with acceleration time histories that are components of HIC, only the 200 g simulated mine tests show a high risk of head injury for the unprotected Hybrid III 50th % male dummy. However, if a 10,000 Hz filter is used as shown in Figure 11, the HIC values increase so that all test conditions now see significantly injurious HIC values well above 1000. This contrast arises since most of the HIC durations were around 1 millisecond as shown in Figure 12. This implies that the basic frequency of the blast event is 1000 Hz or higher. So, the relationship between HIC and actual physical injury for these rapid tests can only be roughly estimated. Thus it is necessary to establish a physical injury model for high rate blunt trauma and correlate it to the dummy model.

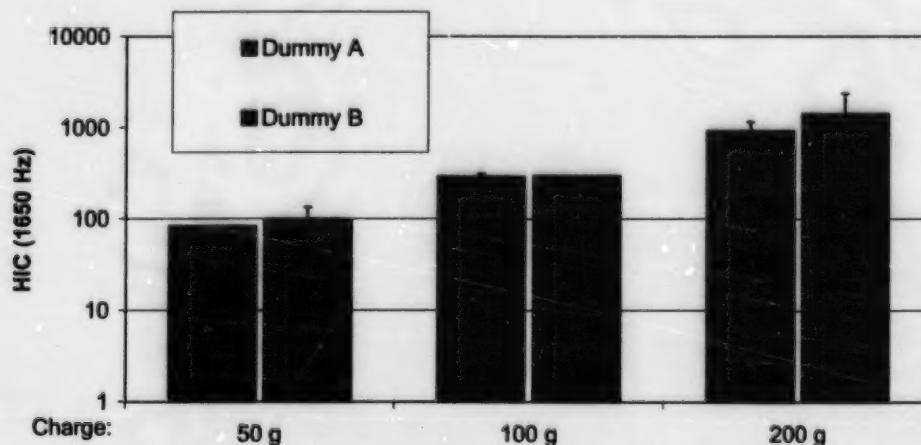


Figure 10: Variation of HIC (1650 Hz) with Unprotected Hybrid III 50th % Male Dummies in the Kneeling Position (Average Values for Repeated Testing)

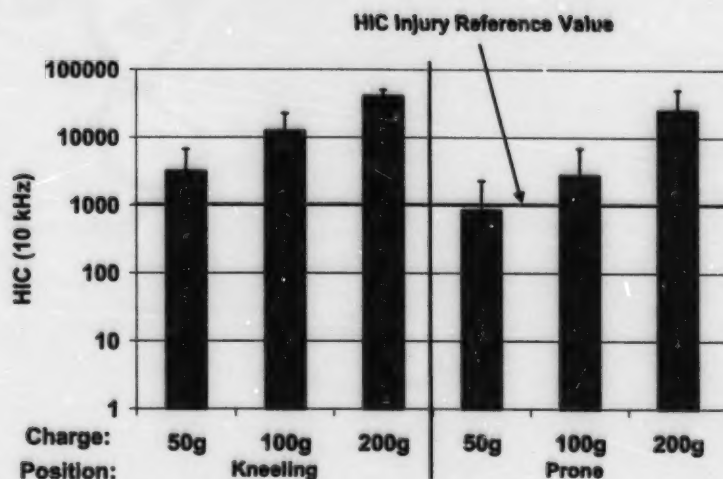


Figure 11: Variation of HIC (10,000 Hz) with Unprotected Hybrid III 50th % Male Dummies in the Kneeling Position (Average Values for Repeated Testing)

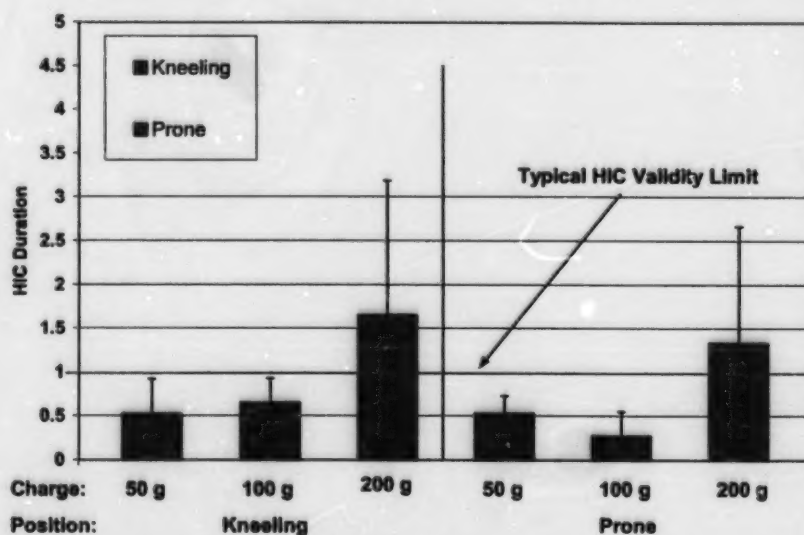


Figure 12: Variation of HIC Duration for Unprotected Hybrid III 50th % Male Dummies in the Kneeling and Prone Positions (Average Values for Repeated Testing)

3.2 Neck Trauma

Neck injuries from blasts are possible owing to different rates of acceleration of the head and of the chest under blast loading. Physical trauma to the neck may be evaluated using the neck force transducers that may be incorporated into the Hybrid III dummy. Barring local damage to the

neck itself, the dynamic impulse in the neck must be transmitted through the relative motion of the head and the chest. This transmission of force is relatively slow compared to the impact of the blast wave. So, neck injuries in blast are similar in rate to impact neck injuries that have been studied in automobile safety and other contexts. There is a proposed neck injury criterion promulgated by the National Highway Traffic Safety Administration (NHTSA) termed the N_{ij} criteria [Eppinger-2000]. The criterion is to be used with Hybrid III dummies.

The N_{ij} criterion is a composite injury indicator based on a linear combination of neck loads and moments. These loads include neck axial tension and compression, and the moments include neck flexion and extension. The postulated injury levels for these combined loads have been validated using human cadaver, volunteer, and animal subjects. N_{ij} is defined as

$$N_{ij} = \frac{F_z}{F_{INT}} + \frac{M_z}{M_{INT}}$$

where F_z is the tension/compression force and M_z is the flexion/extension moment. The values F_{INT} and M_{INT} are the normalization values for the mode of axial force or bending as shown in Table 3. The hexagonal perimeter in Figure 13 represents the Injury Reference Value (IRV) of $N_{ij} = 1.0$ that corresponds to a 30% risk of severe neck injury. The shaded portion is considered acceptable neck loading by this criterion.

Intercept Value	Hybrid III 50 th % Male	Hybrid III 5 th % Female
F_{INT} – Tension (N)	4170	2620
F_{INT} – Compression (N)	4000	2520
M_{INT} – Flexion (N-m)	310	155
M_{INT} – Extension (N-m)	135	67
Peak Tension (N)	6806	4287
Peak Compression (N)	6160	3880

Table 3: Normalized Forces and Moments for N_{ij} Criteria

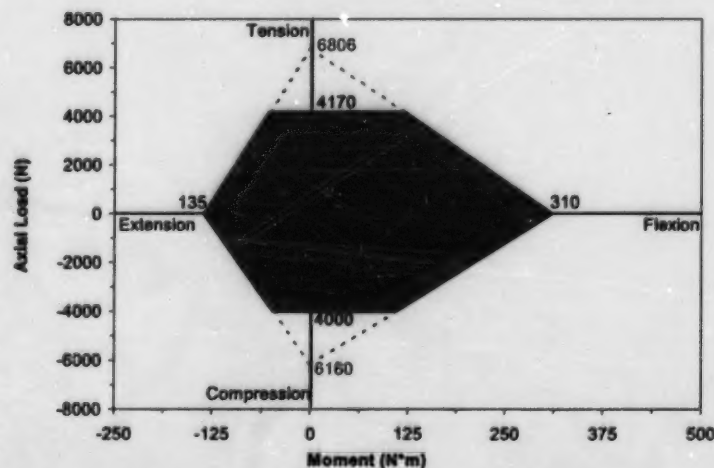


Figure 13: N_{ij} criteria for the 50th percentile male dummy [Eppinger, 2000]

The N_{ij} standard injury predictions were used to assess the effects of the particular dummy used on the test results as shown in Figure 14. Though none of the tests using the unprotected dummies show a high risk of injury indicated by N_{ij} values, there is a significant difference between risk of neck trauma from Dummy A to Dummy B. For matched tests between Dummy A and Dummy B where sufficient tests were available, there was a statistically significant difference between the neck response of the two dummies. The N_{ij} criterion is the sum of the effects of both neck tension/compression axial load and neck flexion/extension moment. However, the configuration of the Hybrid III neck has little axial compliance for loading in tension. For this series of tests, the maximum value of N_{ij} was, on average, a function of 90% neck extension and only 10% tension, and thus, it is highly dependent on the compliance allowed within the neck by the pretensioning setup of the neck.

After the test series was complete, it was determined that the pretensioning bolt supporting the neck for Dummy B was loose, while Dummy A was within specifications. This resulted in a decreased resistance to extension in Dummy B. With a looser neck, Dummy B tended to move out of the blast cone over long times, reorienting the applied load, substantially decreasing the moment. So, only Dummy A was used in further analysis. As this occurred over relatively long times, this did not affect the head accelerations.

Also seen in Figure 14, N_{ij} levels generally increase with charge size and for all tests the 50 g and 100 g charge sizes are statistically significantly different than the 200 g charge size ($p < 0.01$). The prone N_{ij} values are generally larger than the kneeling for two reasons. First, the prone position is 25 cm closer than the kneeling position to the mine blast, though lower in the blast cone. And second, the orientation of the head in the prone tests is more normal to the local blast flow, producing an increased neck moment. So, this result should not be taken as an indication that the prone position has a higher risk of neck injury than the kneeling position for the mines tested.

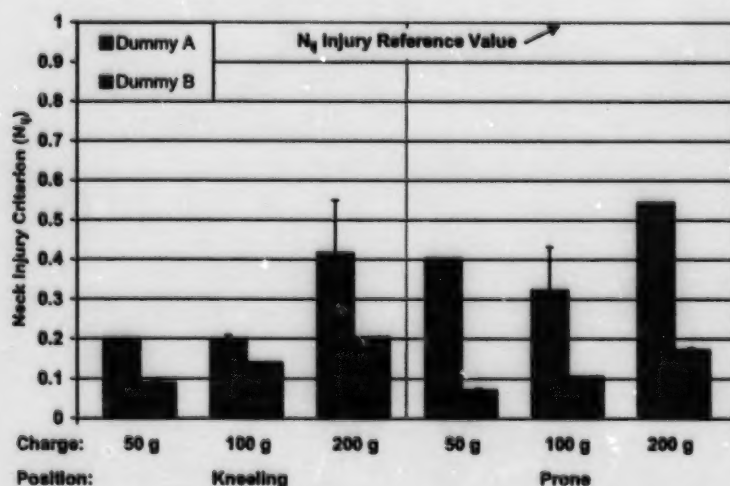


Figure 14: Effect of Dummy for Matched Tests of an Unprotected Hybrid III 50th % Male Dummy In Both Primary Test Positions And At Three Charge Masses.

The strong effect of the blast cone can clearly be seen in additional tests performed at varying distances to the mine and at varying angles within the blast cone. For the kneeling position, two angular positions of the head and two nose-to-mine distances were examined as shown in Figure 15 for a 100 g simulated mine. The tip of the nose was used as a reference point for the head position and the two angular positions were 70° and 65° as measured from the horizontal. The vertical distance to the mine, however, remained relatively constant. The 5° reduction in angle shifts the loading distribution away from the thorax towards the head alone, creating higher relative loads on the head. These higher loads produce higher neck flexion moments.

This result directly contradicts the expectation that increasing radial distance from the blast substantially decreases loading. The 70° position had a 65 cm radial nose-to-mine distance, while the 65° position had a 70 cm radial nose-to-mine distance; the increased distance tended to increase the overall loading in this range of angles and distances. This shows the effect of the strongly conical shock, and the importance of evaluating the effects of the blast cone when assessing injury tolerance using this methodology.

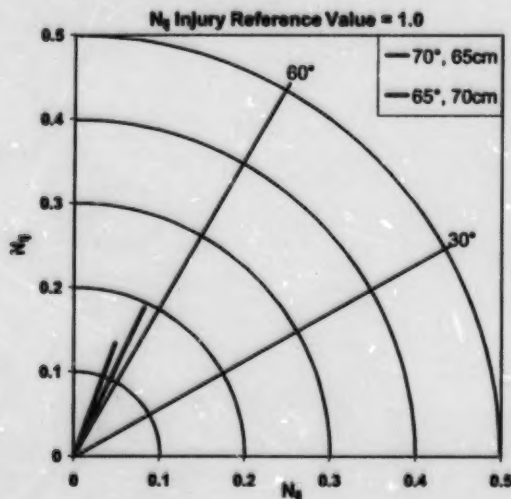


Figure 15: Effect of Dummy Position Relative to the Blast Cone (Kneeling Position, 100-g Charge)

For the prone position with a 200 g simulated mine, three angular positions of the head and three nose-to-mine distances were examined (Figure 16). A constant nose vertical height (33.2 cm) was maintained, and the dummy was moved horizontally relative to the mine position. The tip of the nose was used as a reference for the head and was placed 50 cm, 37.5 cm, and 30.5 cm horizontally from the center of the mine. The reduction in angle for the prone position has a slightly different effect than for the kneeling position. In the prone position there is minimal thoracic loading because of the lower position of the body. Therefore, the reduction in angle simply moves the head further from the conical blast cone, thus reducing the momentum transferred to the head and the neck flexion moment.

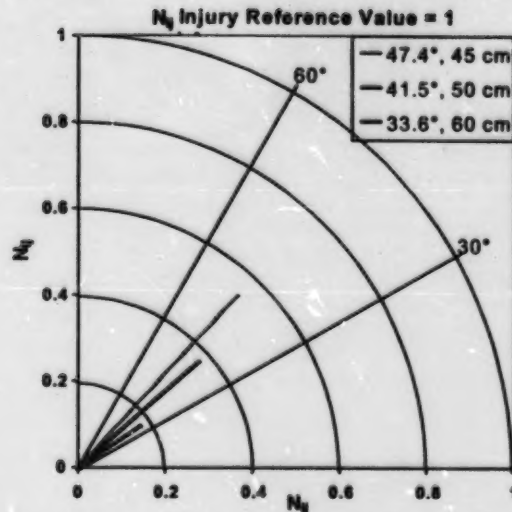


Figure 16: Effect of Dummy Position Relative to the Blast Cone (Prone Position, 200-g Charge)

For all tests conducted, including tests with PPEs, the highest N_{ij} value reported was 0.5, which is well below the 1.0 IRV threshold. So, there is a small risk of serious neck injury for these mine simulants in the positions selected for testing.

3.3 Thoracic Trauma

As mine blasts are rapid events, there are two relevant means to determine the risk of thoracic injury from blunt trauma. These are the displacement of the chest wall, and the viscous criterion (VC). The displacement of the chest wall can be regarded as a surrogate for local strain within the chest. Presumably, the larger the local strain within the chest, the more injurious a local impact. The injury reference value (IRV) for chest displacement in a Hybrid III 50th % male dummy is 63 mm [Eppinger-2000]. The Viscous Criterion (VC) was developed by Viano *et al* [Viano-1988]. This criterion is the product of the velocity of chest wall displacement (V) and the deformation of the chest relative to the initial thickness of the thorax (C). This quantity has been linked with the rate of energy storage in the thorax. A value greater than 1.0 m/s is considered injurious.

Typical values for chest wall displacement are shown in Figure 17. As the impinging blast wave is very rapid, there is no substantial motion of the chest wall. The chest motions for all the unprotected simulated mine tests were less than 1 mm. As the IRV for the Hybrid III is 63 mm, there is a very low risk of displacement strain injuries in this test series. The displacements of the chest are so small that the maximum displacement values are within the range of mid-thorax deformations that may reasonably be measured with the current instrumentation.

For VC, the thoracic displacements are relatively small, and there is no direct measurement of the velocity of the chest. So, the velocity must be calculated either by integrating a sternal accelerometer mounted to the chest wall, or by differentiating the displacement signal. In this test series, the sternal accelerometer was used to obtain the velocity. Though the displacement is

small, the velocity is relatively high for this test series. However, the sternal acceleration measurements did not prove robust for this test series. So, the limited numbers of available values for the viscous criterion are shown in Figure 18 for the unprotected dummy. The values generally increase with increasing explosive blast. Statistical comparison of the differences between dummies is unavailable, however, because of the limited data set.

For this test series, the conical blast pattern limited the risk of injury to the thorax. Neither the sternal displacement nor the VC showed values that could be reasonably construed as injurious.

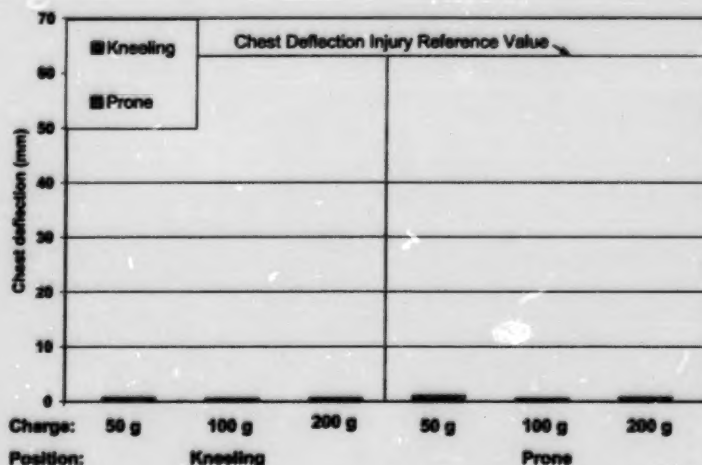


Figure 17: Variation of Chest Maximum Deflection with Unprotected Hybrid III 50th % Male Dummies in the Kneeling and Prone Positions (Average Values for Repeated Testing)

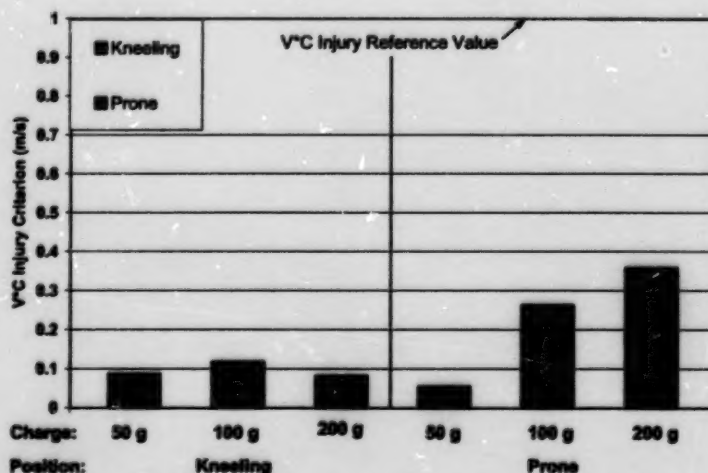


Figure 18: Variation of Viscous Criterion with Unprotected Hybrid III 50th % Male Dummies in the Kneeling and Prone Positions (Average Values for Repeated Testing)

3.4 Burns

As mine blasts involve explosive deflagration, there is a potential for burns close to mine blasts. The mechanism for this injury is rapid radiant and convective heat transfer into the skin. The timescales for this injury, flash burn, are so short that heat transfer from the skin into the body is limited. This test series used an existing skin simulant for evaluating injuries caused by thermal insults [Derkson-1960]. The technique uses a plastic resin 0.05 cm thick with an embedded thermocouple. The temperature output of the thermocouple was correlated with human injury 120 μm below a living skin surface. Low profile cylindrical samples of this skin simulant with embedded thermocouples were used in this test series to evaluate the risk of flash burns from the blast. These skin simulants were attached to the dummy skin at the chin and on the left hand and were exposed directly to the blast in the unprotected tests.

The burn skin simulants proved fragile for the mine blast testing so limited data was collected. The temperature time histories were filtered to 500 Hz to eliminate signals faster than the response time of the thermocouple. These time histories include tests with 4 unprotected hands, including all 3 charge weights used in this series. The chin temperature sensor was used for 9 tests, including 3 unprotected tests at the 100 g and 200 g charge weight, and 6 protected tests using 3 different suits. As there is not sufficient data to differentiate the performance of each suit, they have been lumped together for this analysis.

The induced subcutaneous temperature change in the skin simulant implanted on the dummy hand is shown in Figure 19. This figure includes data from three 100 g tests and a single 200 g test with 42 cm nominal standoff from mine to the hand. Though the average temperature change induced by the blast is substantially larger for the 200 g charge than for the 100 g charge, both are less than 20 $^{\circ}\text{C}$. As the duration of the temperature increase is less than 100 milliseconds in all cases, the risk of injury from severe flash burns to the hand appears to be small. To compare with other widely used injury criteria, a free air temperature of approximately 1100 $^{\circ}\text{C}$ for a duration of 1000 milliseconds is necessary to produce second-degree burns [Ripple-1990].

The induced subcutaneous temperature change in the skin simulant implanted on the dummy chin is shown in Figure 20. Since the number of tests is limited, there is no differentiation between levels of protection of the chin, and the three helmets used are lumped for the analysis. The dummy chin temperature sensor is located approximately 70 cm radially from the center of the mine in the apparent blast cone. For the unprotected chin, the induced temperature change in the sensor increases substantially with charge size. However, as with the dummy hand, the risk of severe burns appears to be quite small, even with unprotected skin contact from the blast. Interestingly, though the face shield on the protected dummy appears to provide some protection to the chin for the 100 g charge size, the induced temperature change for the 200 g charge size is similar to that seen in the unprotected dummy. This result may be the result of loss of the face shield early in the test and a subsequent skin temperature elevation. As the induced temperature differential is likely not injurious for these tests, however, the loss of the face shield during the blast may have limited impact on burn injuries.

The use of the skin simulant with the temperature sensor showed a very small risk of serious flash burns with the explosive and charge sizes used in this testing, even with unprotected skin close to the blast. This was confirmed by the limited burn damage to the dummy skin over a test series of over fourteen unprotected blasts to each dummy head at radial distances as close as 45 cm to the center of the mine. Factors outside this study, however, such as more incendiary explosives, delayed or inefficient combustion, may increase the risk of serious burn injuries in actual mine blasts. Indeed, the depth of burial plays an important role in the amount of afterburn [c.f. Bergeron-1998].

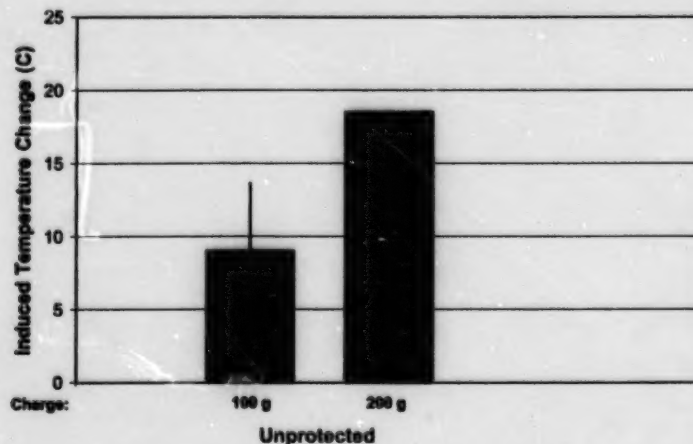


Figure 19: Induced Temperature Change From Blast on Dummy Hand

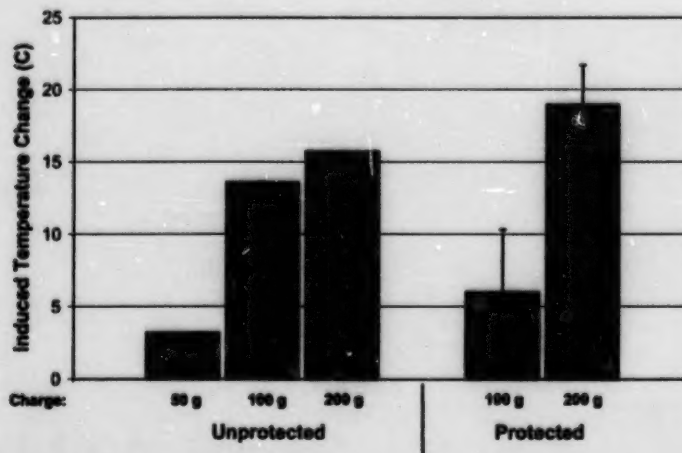


Figure 20: Induced Temperature Change From Blast on Dummy Chin

4. CONCLUSIONS

To summarize, essential elements in the development of a procedure for evaluating the risk of injury while wearing demining protective equipment are:

- Repeatable, quantifiable threat (mine) – with fixed burial and soil characteristics.
- Robust dummy surrogate with established and applicable injury criteria – positioned in a realistic manner in positions representative of demining (i.e. kneeling and prone).
- Accurate positioning – distance to mine must be consistent and quantifiable.
- Robust instrumentation – data handling consistent with the response.
- Reasonable threat level that appropriately identifies the level of protection.

Each of these elements acts to provide an objective criterion for injury and injury performance while ensuring that the resulting criterion is as applicable as possible to the conditions experienced in the real world.

Each of these elements was satisfied in this proposed test methodology. The simulated mines show repeatable pressure time histories, and the largest simulated mine is comparable to an actual mine of the same threat level. Mine burial can be controlled very precisely, and soil characteristics have been fixed.

The Hybrid III dummy has been found to be a robust and repeatable surrogate. None of the dummies used suffered a significant mechanical failure during the testing. The dummies are available in sizes that are anthropometrically similar to a human mid-sized male and similar to a small female. Positioning was accomplished to within ± 3 mm relative to the center of the mine with an inexpensive measurement device. Both the kneeling and the prone positions were specified to produce a significant risk of blunt head trauma to an unprotected dummy.

At first glance, it appears that the prone position has a higher risk of neck injury than does the kneeling position. However, it is important to realize the significant difference in nose-to-mine distance for the two positions. For the kneeling position, the dummy's nose-to-mine distance is 65 cm, whereas for the prone position, the distance is reduced to 45 cm. The two positions were not selected so that the injury risks for the head, neck, and thorax were nearly equivalent, not to directly compare risk of injury between the kneeling and prone positions.

Most of the instrumentation proved robust. For the head and chest accelerometers, the only failures arose from inadvertent wire separation. The head accelerations experienced by the dummies showed a substantial risk of serious head injury from blunt trauma for the larger mines. However, questions remain about the applicability of typical acceleration based injury criteria to mine blasts. It is recommended that a limited test series be performed with an injury model under blast loading to determine the boundaries of applicability of the currently used injury criteria.

The neck sensors performed well. The neck showed forcing similar to that seen in automobile impacts for which the sensors were developed. The sensor data showed good differentiation between the level of mine, and was repeatable within a test dummy. The comparison of Dummy A to Dummy B comparison was compromised by the loosening of the neck of Dummy B. This indicates the large vibration loads in blast shock loading, not seen in the usual automotive application. For future tests, it is strongly recommended that the dummy neck tensioning be checked regularly during the test series.

The thoracic instrumentation proved generally robust. However, neither the chest displacement nor the Viscous Criterion showed injurious values, even for an unprotected dummy. The sternal accelerometers performed poorly, likely owing to high frequency oscillations in the sternum under blast loading. In future testing, the accelerometer should be mounted on the top of the sternum to avoid some of these oscillations.

Burn sensors used on the dummy hand and chin in this testing showed a very small risk of serious burns for the mine simulants and depth of burial used. As the sensors are exceedingly delicate for blast testing, it is recommended that no burn sensors be used in subsequent testing.

Finally, this testing showed the strong effect of the blast cone induced by the geometry of the mines and simulated mines. This conical blast pattern limited the risk of injury to the thorax in both the kneeling and the prone positions. To provide the most comprehensive understanding of this effect, a small test series should be performed to quantify dummy response as a function of position in the blast cone.

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